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DROPLET SIZE CHARACTERISTICS IN HIGH-VELOCITY AIRSTREAMS



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D. E. Franklin

ARO, Inc.

July 1971

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**DROPLET SIZE CHARACTERISTICS
IN HIGH-VELOCITY AIRSTREAMS**

**D. E. Franklin
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32542.

FOREWORD

The work reported herein was sponsored by the Armament Development and Test Center, Air Force Armament Laboratory, Eglin Air Force Base, Florida, under Program Element 62701F, Project 5066.

The results of this study were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), Arnold Air Force Station, Tennessee, under Contract F40600-72-C-0003. The study was made between October 1, 1970, and January 1, 1971, under ARO Project No. RY2137. The manuscript was submitted for publication on April 2, 1971.

This technical report has been reviewed and is approved.

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ABSTRACT

A literature search was conducted to determine (1) if a nozzle system currently exists that would produce large monodisperse (200 to 300 micron) droplets when injecting liquids into a high-velocity airstream (up to 1000 ft/sec), (2) what extent current theories on Aerosol formation can be applied to high-speed dissemination of large, uniformly sized droplets, (3) to what extent these theories have been verified experimentally, and (4) whether additional theoretical and experimental investigations are necessary. A review of many technical publications indicated that the only method currently available for producing the desired droplet size in the specified air velocity is by adding high molecular weight polymers to the base liquid. Analytical and experimental results indicate that, in atomization by high-velocity gas, relative velocity is the most important parameter in determining resulting drop size. Secondary to velocity are viscosity, surface tension, gas and liquid density, and diameter of injector. Most all experimental investigators expressed the need for further research to improve atomization technology. In particular, the greatest need appears to be improvements in the technique for sampling and measuring small droplets.

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NOMENCLATURE

A	Area, in. ²
a	Amplitude, in.
B	$F/\beta^{2/3}$, Composite numerical factor including the sheltering parameter β and parameter F associated with crest configuration at the instant of erosion, both ≤ 1.0
C	Charging factor dependent on electrode spacing, atomizer configuration, etc.
C_{D_o}	Drag coefficient for a cylinder in cross flow
D	Droplet diameter, micron
d	Diameter, in.
E	Voltage
e	A constant, ~ 0.06

FN	Flow number, $Q/(\Delta P)^{1/2}$, gal/min (lb/in. ²) ^{1/2}
f	Frequency, cps
h	Liquid depth, in.
j	Modified sheltering parameter
K	A constant
M	Mass flow rate, lb/sec
m	Assigned constant
P	Pressure, psi
Pe	Electrical pressure, Newtons/(meter) ²
Q	Volumetric flow rate, gal/min
t	Time, sec
V	Relative velocity, ft/sec
α	Angle jet axis makes with free-stream velocity vector
θ	Angle of impingement
λ	Wave length
μ	Viscosity, centipoise and ft ² /sec
ρ	Density, lb/ft ³
σ	Surface tension, lb/ft
ω	Angular velocity

SUBSCRIPTS

Cr	Critical
d	Disk
g	Gas
j	Jet

K	Kinematic
ℓ	Liquid
m	Mass
max	Maximum
n	Diameter, based on number and diameter
o	Orifice
opt	Optimum
orig	Original
s	Diameter, based on number and surface area
sd	Diameter, based on diameter and surface area
v	Diameter, based on number and volume
vd	Diameter, based on diameter and volume
vs	Diameter, based on surface area and volume
\bar{x}	Mean
\bar{x}'	Median
σ	For capillary waves

SECTION I INTRODUCTION

Flight tests were recently conducted at Eglin Air Force Base (Ref. 1) to determine capability for defoliation by high-speed aircraft. Defoliant agent Orange was dispensed at flight speeds between approximately 590 and 760 ft/sec and between 100 and 150 ft above ground level. Measured mass median diameter ranged from 130 to 330 microns (see Appendix II for explanation of drop size). The data indicated that, except for one mission, 81 percent of the collected mass was in droplets of 100 to 500 microns. During two high-speed runs (at approximately 760 ft/sec, flow rates of 300 and 346 gal/min), the greatest percentage of droplet diameters was less than 100 microns. In general, the droplet size was observed to decrease as the airspeed for dissemination was increased.

The wide range of droplet size distribution and the production of very small droplets (less than 100 microns) are both unsatisfactory for efficient defoliation. As a result, a literature survey and an analytical study has been performed (reported herein) to investigate the mechanisms by which liquids are atomized and to determine if there is currently in existence a nozzle system that would produce large (200- to 300-micron droplets), uniform sized droplets when injected into a high velocity airstream (up to 1000 ft/sec). Specific objectives of the study were to (1) determine what extent current theories on aerosol formation can be applied to high-speed dissemination of large, uniformly sized droplets, (2) to what extent these theories have been verified experimentally, and (3) whether additional theoretical and experimental investigations are necessary.

The efforts of this study were primarily limited to consideration of reports pertaining to experimental and analytical investigation of high-speed aerodynamic atomization of liquid jets and droplets. Many reports were reviewed in this study, but the results of only those considered most pertinent are discussed.

SECTION II DISCUSSION

The discussion is divided into two major sections. Initially, in Section 2.1, general atomization techniques are presented. In Section 2.2, a specific type of atomization is discussed in detail—theoretical and experimental aspects of high-speed aerodynamic breakup of liquids (including bulk liquids, jet, and droplets).

2.1 GENERAL ATOMIZATION TECHNIQUES

The characteristics of seven atomization techniques are discussed. Physical parameters relating to droplet size are presented where available. In most cases, the advantages and/or disadvantages of techniques are discussed. Doyle, et al (Ref. 2) presented a comprehensive summary of various techniques for dissemination of chemical agents and is the primary reference source for this section.

2.1.1 Pneumatic Atomization

Pneumatic atomization is accomplished by the effects of a high velocity gas stream on a liquid surface. It is postulated that high velocity gas streams cause wave formations on the liquid surface which crest, form ligaments, and subsequently break into drops. The drop size produced by pneumatic atomization can be varied over a wide range depending on gas velocity. Maximum droplet size, as limited by surface tension, is shown in Fig. 1 (Appendix I) for liquids subjected to different relative velocities (relative velocity between gas and liquid) and ambient pressures. Sonic gas streams can cause breakup of liquids into droplets of 5 microns or less in diameter. The Nukiyama and Tanasawa equation (Ref. 3) is one of the most frequently quoted empirical relationships for pneumatic atomization. It is of the form

$$D_{\bar{x}vs} = \frac{0.186}{V} \left(\frac{\sigma_l}{\rho_l} \right)^{1/2} + 19,700 \left(\frac{\mu_l^2}{\rho_l \sigma_l} \right)^{0.225} \left[\frac{1000 Q_l}{Q_g} \right]^{1.5}$$

where

$D_{\bar{x}vs}$ = Mean volume/surface diameter, microns

V = Relative velocity between liquid and gas, ft/sec

σ_l = Liquid surface tension, lb/ft

ρ_l = Liquid density, lb/ft³

μ_l = Liquid viscosity, centipoise

Q_l and Q_g = Volumetric flow rates for liquid and gas, respectively, gal/min

The equation contains no factor relating to physical configuration (nozzle design), which has been proved significant. An empirical equation for convergent type nozzles was derived by Kim (Ref. 4):

$$D_{m\bar{x}} = \frac{4.8}{A^{0.365} V^{1.144}} \left(\frac{\sigma_l}{\rho_g} \right)^{0.572} \left(\frac{\mu_l}{\sigma_l \rho_l} \right)^{0.161} + \frac{6460}{V^{0.54}} \left(\frac{\mu_l}{\sigma_l \rho_l} \right)^{0.17} \left(\frac{M_l}{M_g} \right)^{0.17}$$

where

$D_{m\bar{x}}$ = Mass mean diameter, microns

A = Flow area for gas, in.²

V = Relative velocity, ft/sec

σ_l = Liquid surface tension, lb/ft

ρ_g = Gas density, lb/ft³

μ_l = Liquid viscosity, centipoise

ρ_l = Liquid density, lb/ft³

M_g and M_l = Mass flow rates for gas and liquid, respectively

y = 1 for $M_l/M_g > 1/3$, and

y = 0.5 for $M_l/M_g < 1/3$.

Pneumatic atomization is a relatively inefficient method for fluid breakup, requiring a high-pressure, high volume gas source. A good filtering system is required to prevent nozzle plugging.

2.1.2 Hydraulic Atomization

Hydraulic atomization is normally accomplished by three basic techniques: (1) swirl nozzles, (2) impinging jets, and (3) jet impaction. In general, hydraulic atomization is the simplest method of fluid breakup. At most hydraulic nozzle operating conditions, internal jet turbulence is predominant in liquid disintegration. At low injection pressure, external forces such as air resistance are instrumental in breakup. As pressures and flow rates are increased, liquid turbulence plays an important part. Injection pressures sufficiently high will cause jet breakup, even when ejected to a vacuum.

2.1.2.1 Swirl Nozzles

The swirl nozzle configuration produces the smallest particle size of any hydraulic-type nozzle. Fluids discharged from this type nozzle are imparted at high velocity with a circular motion resulting in a conical sheet formation. Factors affecting droplet size from a swirl nozzle injector are flow rate, nozzle design, liquid pressure, fluid viscosity, fluid surface tension, and ambient atmospheric conditions. Viscosity is the major factor in determining drop size if external ambient velocities are insignificant. An equation that Lapple, et al (Ref. 5), suggests to describe swirl nozzle performance is

$$D_{\bar{x}vs} = \frac{13.0 d_o^{0.55} \mu_l^{0.20} \sigma_l^{0.25}}{V^{0.70} \rho_l^{0.45}}$$

where

$D_{\bar{x}vs}$ = Volume/surface mean diameter, microns

d_o = Diameter of discharge opening, in.

μ_l = Liquid viscosity, centipoise

V = Relative velocity between liquid and gas, ft/sec

ρ_l = Liquid density, lb/ft³

2.1.2.2 Impingement Jets

Impinging jets promote fluid breakup by directing liquid jet streams together. A flat liquid sheet is formed perpendicular to the plane of jets which then disrupts into droplets. Published data on impinging jets are limited and somewhat inconsistent. Fry (Ref. 6) states that mass median diameter from impinging jets can be described in the form (units not given):

$$D_{m\bar{x}}' = K_1 + K_2 V \sin \theta/2$$

where

$D_{m\bar{x}}'$ = Mass median diameter

K_1 = Constant

K_2 = Constant

V = Velocity

θ = Angle of impingement

2.1.2.3 Jet Impaction

Fluid breakup results when a liquid jet or sheet impacts on a solid surface and is then deflected parallel to the surface. Although little information exists relating drop size to system parameters, an empirical equation suggested by Fraser (Ref. 7) is

$$D_{m\bar{x}}' = 379 \left[\frac{FN}{\Delta P} \right]^{1/3}$$

where

$D_{m\bar{x}}'$ = Mass median diameter, microns

FN = Flow number = $Q_l/(\Delta P)^{1/2}$

Q_l = Liquid flow rate, gal/min

ΔP = Pressure differential, psi

2.1.3 Rotating Disk Atomization

Rotating disk atomization can include flat disk, cones, cups, and bowls. The rotating device is spun at high angular velocity (see Fig. 1 for gravitational effect on maximum

droplet size). Centrifugal force interacting with liquid surface tension results in atomization at the disk periphery. At low liquid flow rates, drops form directly at the disk edge. As flow rate is increased at a constant angular velocity, ligaments are thrown off at the disk edge. These ligaments are unstable and break into droplets. At high flow rates, the number and the size of the ligaments increase until finally a continuous film forms which extends from the disk edge. For low to moderate flow rates, uniform droplet sizes can be expected. At higher flow rates, a heterogeneous drop size distribution is produced. An equation for low to moderate flow rates defined by Walton and Prewett (Ref. 8), modified by dimensional analysis with an equation arrived at by Hinze and Milborn (Refs. 2 and 9), led to an experimental expression for drop diameter:

$$D_{\bar{x}} = 0.01 (d_d) \left(\frac{\mu \ell^2}{\rho \ell \sigma \ell d_d} \right) \left(\frac{\omega^2 (d_d)^3 \rho \ell}{\sigma \ell} \right)^{-0.522}$$

where

$D_{\bar{x}}$ = Mean drop diameter, microns

d_d = Disk diameter, in.

$\mu \ell$ = Liquid viscosity, centipoise

$\rho \ell$ = Liquid density, lb/ft³

$\sigma \ell$ = Surface tension, lb/ft

ω = Angular velocity, radians/sec

This method of atomization is not subject to orifice plugging and can be utilized with highly viscous fluids. Dynamic balance is critical, and for small droplet production, large disks are required with added weight problems.

2.1.4 Whistle Nozzle (Sonic or Hartman Whistle)

Whistle nozzles differ from a conventional pneumatic atomizer in that air is sonically vibrated when contacted with the liquid. Smaller droplet sizes can be generated by the whistle nozzle than with conventional pneumatic atomization methods. Sonic or supersonic gas from a nozzle forms alternate compression and rarefactions when it impinges on a resonant cavity or disk, resulting in reinforced pulsations of sonic or supersonic frequencies. Replacement of the resonant cavity of the Hartman whistle by a flat plate or button can result in a standing shock wave.

Little experimental or theoretical data exist describing relationship of droplet size to system parameters.

2.1.5 Electrostatic Atomization

Droplets can be produced by electrostatic atomization if the electric field is sufficiently high. Atomization off sharp edges can be produced eliminating orifice

requirements and possible plugging. Conductivity of the liquid is the dominating variable in aerosol formation. Droplet diameter can be expressed as (Ref. 2):

$$D_{\bar{x}} = 2 \times 10^6 \left[\frac{K C E^2}{P_e 8 \pi} \right]^{1/4}$$

where

$D_{\bar{x}}$ = Mean drop diameter, microns

K = (Coulomb)²/9 x 10⁹ Newton-(meter)²

C = Charging factor and is dependent on electrode spacing, atomizer configuration, etc.

E = Volts

P_e = Electrical pressure, Newtons/(meter)²

Flow rates are extremely low for this method of atomization.

2.1.6 Ultrasonic Atomization

Atomization by the ultrasonic method is promoted by sonically vibrating a liquid surface which induces pressure variations into the liquid. This can be accomplished by submerging a transducer into a reservoir of liquid and directing sonic energy to the surface or by placing a thin liquid film directly in contact with a vibrating surface. Waves form in the liquid surface which grow until instability occurs and wave crests break off to form drops. Flow rate is low, up to approximately 0.0125 gal/min. A dimensionless equation that expresses droplet diameter was proposed by Peskin and Raco (Ref. 10) as

$$D_{\bar{x}} = \pi a \left[\left(\frac{\sigma \ell}{2 \rho \ell \pi^2 f^2 a^3} \right)^2 \tanh \left(\frac{\pi a}{D_{\bar{x}}} \right) \left(\frac{h}{a} \right) \right]^{1/3}$$

where

$D_{\bar{x}}$ = Mean diameter

π = 3.142 radians

a = Wave amplitude

$\sigma \ell$ = Surface tension

$\rho \ell$ = Liquid density

$f =$ Drive frequency

$h =$ Liquid depth

Ultrasonic atomization systems are generally expensive and relatively heavy.

2.1.7 Mechanical Atomization (Vibrating Reed, etc.)

Mechanical atomizer configurations include liquid flow (1) internally through a hollow vibrating reed and (2) externally onto a vibrating reed fed by a stationary capillary. Atomization results from shear forces and impaction on acceleration surface. Production of small droplets by this method is contingent upon a low liquid flow rate.

2.2 AERODYNAMIC BREAKUP OF LIQUIDS

2.2.1 Theoretical Aspects - Liquid Jet Atomization

Breakup of liquid jets by aerodynamic forces has been described (Ref. 11) as occurring in three modes: (1) at low gas velocity, interplay of inertia and surface tension results in the jet becoming varicose (axial symmetrical waves that grow and eventually break into drops), (2) at slightly higher velocities, the jet becomes sinuous and air resistance becomes more important than surface tension, and (3) at velocities in excess of a critical value, the jet is completely disrupted and breakup is controlled by viscous and inertia forces. Item 2 is described as an intermediate step, with a slight change in conditions being sufficient to convert this type into the first or third type of breakup. The velocity regime considered in this report is in the high subsonic region where the third type of jet breakup dominates.

High relative gas to liquid velocity initially causes wave or ripple formation on the liquid surface. It is postulated that these waves crest as the amplitude approaches the wave length and that the gas stream will erode the wave crest as ligaments from which droplets of diameter proportional to wave lengths are formed. There exists a spectrum of wave lengths that can be excited to an amplitude sufficient for the aerosolization process; however, an optimum wave length (λ_{opt}) will predominate and grow faster than others (this, of course, depends on the existing physical conditions and is discussed in subsequent sections). Liquid droplet size will vary over a wide range in the process of atomization by a high velocity gas stream, primarily because (1) wave lengths other than optimum form as previously discussed, (2) a portion of the jet may be partially sheltered from gas velocity in some areas, (3) there may be some coalescence of drops, and (4) evaporation may be a factor.

Two types of waves, acceleration and capillary, are proposed as existing on the liquid surface when atomized by a high gas velocity. Acceleration waves are formed at velocities higher than capillary waves, and Adelberg (Ref. 12) states that acceleration waves dominate when the wave length exceeds a critical magnitude defined by:

$$\lambda_{cr} = \left[\frac{\pi^3 \sigma d_j}{C_{D_0} (\sin^2 \theta) \frac{1}{2} \rho_g V_g^2} \right]^{1/2}$$

where (using consistent units)

λ_{cr} = Critical wave length

σ_l = Surface tension

d_j = Liquid jet diameter

C_{Do} = Drag coefficient for a
cylinder in cross flow

θ = Angle that jet axis makes
with free-stream velocity
vector

ρ_g = Gas density

V_g = Gas velocity

Capillary waves dominate below this critical value.

Mayer (Ref. 13) developed an expression for mean droplet size assuming capillary waves predominate. The equation,

$$D_{\bar{x}} = 22.6(\pi)(B) \left(\frac{\mu_l [\sigma_l / \rho_l]^{1/2}}{\rho_g V_g^2} \right)^{2/3}$$

where (using consistent units)

$D_{\bar{x}}$ = Mean droplet diameter

$B = F/\beta^{2/3}$, a composite numerical factor
where F is a parameter associated with
the crest configuration at the instant
of erosion, and β is a sheltering param-
eter associated with the portion of the
wave crest exposed to the wind effects
(F and $\beta \leq 1.0$)

μ_l = Dynamic liquid viscosity

σ_l = Surface tension

ρ_l = Liquid density

ρ_g = Gas density

V_g = Gas velocity

was developed for an infinitely large, flat surface (large compared with wave length). Consequently, any effects of finite orifice diameter on droplet size are neglected. Adelberg (Ref. 12) elaborated on Mayer's results by considering jets of a finite diameter and calculated relationships for acceleration as well as capillary waves. His results indicated that for

(1) Capillary waves

$$D_{\bar{x}} = 2.4(d_{j_{max}})^{1/2} \left[\frac{\mu_l (\sigma_l / \rho_l)^{1/2}}{\beta \rho_g V_g^2} \right]^{1/2} \left[\frac{1 - K_3 \beta (\pi/2)^{1/2} e^{3/2}}{5 j_\sigma} \right]$$

where (using consistent units)

$D_{\bar{x}}$ = Mean droplet diameter

$d_{j_{max}}$ = Maximum diameter of liquid jet

μ_l = Liquid viscosity

σ_l = Surface tension

ρ_l = Liquid density

β = Jeffrey's sheltering parameter
having value between 0 and 1.0
(Adelberg suggests 1.0)

ρ_g = Gas density

V_g = Gas velocity

K_3 = Proportionality constant, 1.0

e = A constant, ~ 0.06

j_σ = Modified sheltering parameter
for capillary waves

and (2) Acceleration waves

$$D_{\bar{x}} = 65.3 \left[\frac{\mu_l (\sigma_l / \rho_l)^{1/2}}{\beta \rho_g V_g^2} \right]^{2/3}$$

where

β = 1.0 and other parameters are
as defined in (1) for capillary
waves.

As can be noted, Adelberg's result for acceleration waves compares closely with Mayer's analysis for capillary waves, while Adelberg's analysis of capillary waves is quite different. Adelberg explains this by stating, "One of the reasons for the similarity between the present results for the acceleration wave regime and Mayer's result (for the capillary wave regime) is that the minimum wave length for the two regimes is nearly the value which results if capillary forces are assumed, as Mayer did, always to dominate. For the acceleration wave regime, the mean drop size is proportional to the minimum wave length, and the orifice diameter plays a negligible role."

2.2.2 Theoretical Aspects—Droplet Breakup

There is a critical gas velocity, depending on fluid characteristics and droplet diameter, that will create external aerodynamic forces higher than surface tension forces and cause droplet deformation. Velocities greater than a critical value will cause the flattened droplet to be blown out in a concave manner into the form of a hollow bag attached to a circular rim. Bursting of the bag (containing approximately 30 percent of the original droplet) produces very fine droplets, while the rim (containing approximately 70 percent of the original drop) will break into larger drops.

Gas velocities greatly in excess of the critical value will cause stripping or shearing of the droplet by the mechanism previously discussed for jets exposed to a high velocity gas stream, i.e., wave formations that crest, forming sheets or ligaments that break into droplets. Although shear breakup dominates in the higher velocity regime, a combination of bag and shear breakup can occur.

The maximum possible droplet size (exposed to a gas velocity) is limited by surface tension. This size is limited by the equation (Ref. 14):

$$D_{\max} = \frac{2.44 \times 10^6 \sigma g}{\rho_g V^2}$$

where

D_{\max} = Maximum stable droplet size,
microns

σ = Surface tension, lb/ft

g = Gravitational constant, ft/sec²

ρ_g = Gas density, lb/ft³

V = Relative velocity, ft/sec²

This equation does not account for viscous effects. The formation of a liquid particle can be delayed by viscous forces, and the velocity loss of the droplet can become so great that the relative velocity will drop below the critical velocity before a rupture takes place. The critical velocity is also a function of the method applied; critical velocity for

a gas stream suddenly applied is less than for a gradually increasing velocity. Critical velocities versus droplet size for three liquids are shown in Fig. 2 (Ref. 14). It is assumed that velocity is of a continuously increasing nature. Ambient pressure also affects the critical velocity droplet size relationship. As the ambient pressure is increased, the velocity required to reduce the droplet size is decreased (Ref. 15).

Wolfe and Andersen (Ref. 16) emphasized droplet breakup as a rate process and discussed application of kinetic theory to the breakup process. Most of the previous work had considered droplet breakup from a hydrodynamic and mechanical approach; inclusion of kinetic theory makes the method of droplet breakup more dependent on breakup time. For negligible viscosity and surface tension (extremely high gas velocity), breakup time could be shown to be (using consistent units):

$$t = \frac{D}{V} \left(\frac{\rho_l}{\rho_g} \right)^{1/2}$$

where

t = Time

D = Original drop diameter

V = Relative gas velocity

ρ_l = Liquid density

ρ_g = Gas density

For a highly viscous fluid and negligible surface tension, breakup time would be defined by

$$t = \frac{32 \mu_l}{\rho_g V^2}$$

where

t = Time

μ_l = Liquid viscosity

ρ_g = Gas density

V = Relative gas velocity

They derived the following expression for aerodynamic breakup of a liquid drop as (again using consistent units):

$$D_x = \left[\frac{136 \mu_l \sigma_l^{3/2} D_{orig}^{1/2}}{\rho_g^2 \rho_l^{1/2} V^4} \right]^{1/3}$$

where

$D_{\bar{x}}$ = Mean diameter of droplets produced by breakup of the original drop

σ = Surface tension

Other parameters are as noted above. The equation was derived for conditions where aerodynamic forces are much larger than viscous and surface tension forces. If either is significant, the various approximations indicated in the derivations would require more exact approximations. The equation generally agrees with the theoretical equations developed by Mayer and Adelberg for aerodynamic breakup of liquid jets.

2.2.3 Experimental Results—Liquid Jet and Droplet Atomization

The experimental results obtained by Weiss and Worsham (Ref. 17) are frequently referenced by analytical investigators for comparison of results. Weiss and Worsham injected molten wax into heated airstreams at high subsonic velocity. Droplets resulting from atomization were cooled to the solid state, and their size and distribution were determined. Variables introduced and their ranges were (1) relative air velocity, 200 to 1000 ft/sec, (2) liquid injection velocity, 4 to 100 ft/sec, (3) injector diameter, 3/64 to 3/16 in., (4) liquid viscosity, 3.2 to 11.3 centipoise, (5) air static pressure from 1 to 5 atmospheres, and (6) both costream and contrastream injection. The results of their experimental investigation were summarized by the proportion:

$$D_{m\bar{x}'} \approx V^{-1.33} V_l^{0.08} d_o^{0.16} \mu_l^{0.34} \left[1 + \frac{\rho_{g0}}{\rho_g} \right]$$

where

$D_{m\bar{x}'}$ = Mass median diameter, microns

V = Relative velocity, ft/sec

V_l = Liquid injection velocity, ft/sec

d_o = Injector diameter, in.

μ_l = Liquid viscosity, centipoise

ρ_{g0} = Density of air at 300°F, lb/ft³

ρ_g = Gas density, lb/ft³

Three parameters not varied were surface tension, air viscosity, and liquid density. The authors used dimensional analysis to arrive at the proportion:

$$D_{mx'} \approx [\sigma_l^{0.41} \mu_g^{0.09} \rho_l^{-0.84}] [0.0195]$$

where

σ_l = Liquid surface tension, lb/ft

μ_g = Air viscosity, centipoise

ρ_l = Liquid density, lb/ft³

Combining this with the empirically derived equation, they arrived at the dimensionless result:

$$\frac{D_m \bar{x} \rho_g V^2}{\sigma_l} = 0.0115 \left(\frac{V \mu_l}{\sigma_l} \right)^{2/3} \left(1 + \frac{10^3 \rho_g}{\rho_l} \right) \left(\frac{M_l \rho_l \sigma_l \mu_g}{\mu_l^4} \right)^{1/12}$$

where

M_l = Mass injection rate, lb/sec

The approximate droplet size (mass median diameter, microns) at relative velocities of 400 and 1000 ft/sec for three orifice sizes (interpolated from their velocity versus droplet size figures) were:

<u>Tube diameter, in.</u>	<u>Droplet size, microns</u>	
	<u>V = 400 ft/sec</u>	<u>V = 1000 ft/sec</u>
3/64	60	20
3/32	70	22
3/16	75	22

One surprising trend observed by Weiss and Worsham was an increase in droplet size as injection velocity was increased (for costream and contrastream injection). The effect was small (proportional to $V^{0.08}$), but it should be investigated further to determine if droplet size could be significantly increased by reducing relative velocity in this manner.

Weiss and Worsham noted that the smallest diameter orifice (3/64 in.) produced unusual results at low relative velocities (approximately 200 to 400 ft/sec) and low liquid injection velocities. They stated, "It is likely that a different mechanism of atomization begins to become important for these small tubes at low liquid and air velocities."

Weiss and Worsham concluded their report by stating "the atomization of liquids by large high velocity airstreams occurs by direct action of the airstream on the exposed liquid surface. Therefore, relative velocity between liquid and airstreams is of primary importance. Physical properties of the fluids do affect spray fineness, but their net influence is less critical. The exact way in which the liquid is introduced to the air, i.e., the geometry and operation of the injector, is of least importance, particularly at very high air velocities and for customary ranges of the variables."

Merrington and Richardson (Ref. 11) conducted tests using liquids with different viscosity and surface tension values. The relative gas velocity in these tests was moderate (up to approximately 330 ft/sec). The injector nozzle diameter was varied from 0.4 to 0.7 in. The droplets generated were collected on thin blotting paper, and the measured diameter was corrected by a known constant. The results obtained led them to the conclusion, "In every case the mean drop size was found to depend only on the relative speed of the jet to the air and on the viscosity of the liquid." Their results satisfied the empirical equation:

$$D_{\bar{x}} = \frac{0.0389 \mu_{\ell K}^{1/5}}{V}$$

where

$D_{\bar{x}}$ = Mean drop size, microns

$\mu_{\ell K}$ = Liquid kinematic viscosity, ft^2/sec

V = Relative velocity, ft/sec

which they state is dimensionally unsound but could be corrected by including a term involving the kinematic viscosity of the surrounding medium (which was not varied and thus omitted).

Nukiyama and Tanasawa (Ref. 3) developed an empirical equation for small pneumatic nozzles with which most investigators (both analytical and experimental) compare results. Their data led to the relationship:

$$D_{\bar{x}vs} = \frac{0.186}{V} \left(\frac{\sigma_{\ell}}{\rho_{\ell}} \right)^{1/4} + 19,700 \left(\frac{\mu_{\ell}^2}{\rho_{\ell} \sigma_{\ell}} \right)^{0.225} \left[\frac{1000 Q_{\ell}}{Q_g} \right]^{1.5}$$

where

$D_{\bar{x}vs}$ = Mean volume/surface diameter, microns

V = Relative velocity, ft/sec

σ_{ℓ} = Surface tension of liquid, lb/ft

ρ_{ℓ} = Liquid density, lb/ft^3

μ_{ℓ} = Liquid viscosity, centipoise

Q_{ℓ} and Q_g = Volumetric flow rates for liquid and gas, respectively

Liquid flow rate for these experiments was very small (approximately 0.01 gal/min). As can be noted from the empirical equation, droplet size increases as the liquid flow rate is increased or as the air flow rate is decreased. These experimenters found the droplets smaller at the fringes of the jet than in the center.

Chen and Kevorkian (Ref. 18) reported experimental results of producing 300-micron droplets with two-phase air-water nozzles. The ranges of operating conditions were supply pressures of air (30 to 100 psig) and water (30 to 125 psig) and flow rates of air 125 scfm and water 2 to 32 gal/min. The gas velocity at the nozzle throat was quoted as ranging from a minimum of 564 ft/sec to sonic (956 ft/sec). They stated that the true value was somewhere between these two, depending on water flow rate. They calculated the water velocity to be about 130 ft/sec, estimated a stay time in the diffuser section of 0.004 sec, and stated that this time was too short to appreciably accelerate the water. The water droplet size was dependent on water flow, ranging from about 150 microns at 2 gal/min to 300 microns at 32 gal/min. A question that immediately comes to mind is why such large droplets in this case when the quoted relative velocity is large enough to permit a maximum size of 30 microns if the surface tension criteria is used (see Section 2.2.2 and Fig. 2). The answer could involve one or a combination of the following: (1) the quoted relative velocity decreases rapidly and a great part of the liquid is atomized at a much lower velocity, (2) coalescence of droplets may have occurred, and (3) the central portion of the jet may not have been subjected to the total effects of the quoted velocity.

Davidson (Ref. 19) reported the results of droplet size measurements in a high-velocity airstream using in-line holographic photography. In these tests, a simulated defoliant spray was injected into a 675 ft/sec airstream; flow rates were varied from 3 to 117 gal/min, and injection pressures were from 16 to 64 psig. The injector diameter varied from 0.152 to 1.079 in. The average diameter of spray droplets was approximately 21 microns, with little or no variation attributable to flow rate, injection pressure, or injector diameter.

Hanson, Domich, and Adams (Ref. 20) conducted droplet breakup experiments with methyl alcohol, water, and three solutions of silicone oil (kinematic viscosity ranged from 0.696 to 100 centistokes and surface tension from 0.00138 to 0.00493 lb/ft). Their results indicated that the critical gas velocity was proportional to the one-third power of surface tension. Their results also indicated that "the effect of liquid viscosity on the critical breakup velocity is negligible for viscosities of about 10 centistokes or less. Between 10 and 100 centistokes the effect is substantial, increasing the critical velocity approximately 70 percent in the case of a 150-micron drop of the maximum viscosity." They further state "for viscosities between 50 and 100 centistokes, the effect of increasing viscosity on critical velocity becomes more pronounced as drop diameter decreases."

2.2.4 Experimental Results of Efforts to Produce Larger Droplets in Pneumatic Atomization

Karp and Wachtell (Ref. 21) reported results of tests conducted for the Army Chemical Warfare Laboratory, U. S. Army Chemical Center, Maryland. Their study was limited to the addition of four high molecular weight polymers to dibutyl phthalate. Preliminary experiments indicated best results with Rohm and Haas polyisobutyl methacrylate (PIBMA). Concentrations of this polymer in dibutyl phthalate was varied from 0 to 0.75 percent by weight. Capillary injection diameters of 0.049 and 0.026 in. were used for solution dissemination into a high velocity gas stream (Mach No. 0.85 or 970 ft/sec). The effects on droplet size of 0.125, 0.25, 0.5, and 0.75 percent of Rohm and Haas PIBMA (with 0.049-in. diameter capillary) is shown in Fig. 3. Droplet size with pure dibutyl

phthalate increased from 27 microns (50 percent of cumulative spray sample less than 27 microns) in the 0.85 Mach No. airstream to 400 microns with 0.5 percent Rohm and Haas PIBMA. Another test was conducted at similar conditions except the injector orifice was 0.026 in. The droplet size (27 microns) of pure dibutyl phthalate was identical for both orifice diameters. However, with 0.5-percent Rohm and Haas PIBMA the droplet size was 150 microns for the 0.026-in. orifice as opposed to 400 microns with the 0.049-in. orifice. A small decrease in droplet size would be expected with an orifice size decrease. However, the decrease from 400 to 150 microns appears to be excessive. Apparently, the effect on droplet size of extremely small injection orifices, previously described by Weiss and Worsham (Section 2.2.3), is a factor in this case.

Nash, Hanson, and Grimm (Ref. 22) reported tests conducted for the U. S. Army Biological Laboratory, Fort Detrick, Frederick, Maryland. Objectives were to determine the influence of wind velocity, nozzle configuration, and fluid properties on drop size distribution. These tests were accomplished using (1) nine commercial spray nozzles (orifice diameter ranging from 0.041 to 0.250 in.), (2) a mixture of fuel oils to simulate viscosity or agent Purple defoliant, (3) various weights of motor oils to evaluate viscosity effects, (4) addition of two fatty acid derivatives to oils for surface tension studies, and (5) a thickened water solution with greatly increased viscosity. Gas velocity effects of approximately 120, 250, and 500 ft/sec were evaluated. In general, the simplest nozzle, a vee jet (straight tubular section flared at both ends) or a simple orifice produced the largest drops. The authors stated that velocity and surface tension effects agreed with those found by Weiss and Worsham (Ref. 17), but viscosity effects were not conclusive (it was suggested that viscosity effects may have been negated by the low flow rates observed with the more viscous fluid). Thickened water solutions (1-percent Cellosize® QP-5200D and 1-percent Kelzan) produced droplets larger than those for Purple simulant. The 1-percent Kelzan solution produced the largest droplets of any liquid sprayed (viscosity of this mixture is less than the Cellosize mixture). Droplet sizes for the different solutions at about 505 ft/sec gas velocity were

<u>Solution</u>	<u>Pressure, psi</u>	<u>Droplet Size, $D_{m\bar{x}}$, microns</u>
Purple Simulant	42	84
Water	26	94
1-percent Cellosize	23	114
1-percent Kelzan	22	185

It should be pointed out that the relative velocity (between gas and liquid) is less than 505 ft/sec. Velocity of liquid, costream injected, was not subtracted from the gas velocity.

Klein and Harrigan (Ref. 23) documented results of a comparison study of Stull Bifluid defoliant system with the conventional Orange defoliant system. The difference between Stull Bifluid configuration and the standard Orange system was stated as:

- Standard Orange System - Used agent Orange with A/A454-1 spray system with open check valve
- Stull Bifluid System - Modified A/A454-4 spray system with Whirljet® 3/8 BX20 slope bottom nozzles installed on check valves

The Stull Bifluid defoliant consists of agent Orange plus a chemical additive, which, when mixed in the spray system pump with a second liquid during agent dissemination, produces the gel defoliant. Agent recovery, droplet size, and distribution were of primary concern. Fluids were disseminated from an aircraft at an indicated airspeed of approximately 250 ft/sec. The authors concluded from the test results that the conventional system was more satisfactory since (1) ground distribution with the standard Orange system was much better than with Stull Bifluid (approximately twice the ground area covered with the minimum 1 gal/acre with standard Orange defoliant than with Stull Bifluid) and (2) average mass median diameter was not significantly different with either system (329 microns with standard Orange and 344 microns with Stull Bifluid).

A two-fluid atomization system was experimentally tested (Ref. 24) in which foam was added to water and the mixture converted into a thin film before introduction to the nozzle. In experiment, liquid was fed from the center of a nozzle as a foam, with high velocity air (sonic) supplied to an annulus surrounding the tube. Droplets produced by this method were approximately two times larger than experienced without foam.

SECTION III RESULTS

A review of analytical and experimental efforts in the field of atomization techniques indicated that there is not currently available a dissemination method that will satisfactorily meet specified requirements (production of monodisperse 200- to 300-micron droplets in airstream velocities up to 1000 ft/sec). All investigators have concluded that, in pneumatic atomization of liquids (in high gas velocity systems), gas velocity is the most important factor in determining resulting droplet size; fluid and injector characteristics are less significant in comparison. A comparison of analytical results (arrived at by Mayer, Ref. 13, and Adelberg, Ref. 12) with experimental results (Weiss and Worsham, Ref. 17) indicates that the droplet size is proportional to (velocity)^{1.33}. In highly viscous liquids, viscosity is the second most important parameter in controlling droplet size. Experimental results of Weiss and Worsham indicate that the droplet size is proportional to (viscosity)^{0.34}, where analytical results indicate approximately (viscosity)^{0.66}. These were moderate to low viscosity liquids, where viscous effects are less pronounced. Merrington and Richardson (Ref. 11) concluded from their test results that mean droplet size depended only on relative velocity and liquid viscosity. Analytical results of Mayer (Ref. 13) and Adelberg (Ref. 12) and experimental results by Weiss and Worsham (Ref. 17) indicate that surface tension affected droplet size by the proportion (surface tension)^{0.33}. Several investigators stated that orifice diameter had no effect at high velocity, but the results of Weiss and Worsham indicated a proportion of (diameter)^{0.16}. Analytical results for liquid and gas density

effects were (liquid density)^{-0.33} and (gas density)^{-0.66}. Experimental results indicated proportions of (liquid density)^{-0.5} to ^{-0.225} and (gas density)^{-1.5}. Weiss and Worsham also noted in their tests that droplet size was proportional to $(Vg)^{0.08}$.

Parameter exponents are summarized from results of two experimental and three theoretical analysis as follows:

Independent Variable	Weiss and Worsham (Ref. 17) ⓑ	Nukiyama and Tanasawa (Ref. 3) ⓒ	Wolfe and Andersen (Ref. 16) ⓓ	Mayer (Ref. 13) ⓔ	Adelberg (Ref. 12) ⓑ
Droplet Size Definition	$D_{mx'}$	D_{xvs}	D_x^-	D_x^-	D_x^-
Relative Velocity	-1.33	-1 to -2.5	-1.33	-1.33	-1.33
Liquid Viscosity	0.34	0.45	0.33	0.67	0.67
Gas Density	-0.7	-1.5	-0.67	-0.67	-0.67
Surface Tension	ⓐ	0.50 to -0.225	+0.50	0.33	0.33
Liquid Density	ⓐ	-0.5 to -0.225	-0.17	-0.33	-0.33
Orifice Diameter	0.16	0	0	0	0
Liquid Velocity	0.08	—	—	0	0

- ⓐ Experimental determination not made
- ⓑ Liquid jet injected into high velocity gas stream
- ⓒ Two-fluid (water-air) nozzle
- ⓓ Droplet atomized by high velocity gas stream
- ⓔ Bulk liquid atomized by high velocity gas stream

There have been experimental tests in which high molecular weight polymers were added to a base liquid. Additives of this nature appreciably thicken and increase viscosity of the base liquid and result in larger droplets when atomized by high velocity gas. This

method would appear to require further development to more reliably predict droplet size and distribution pattern.

Several of the authors referenced in this report have indicated the need for further development work in the field of atomization. The most pressing need appears to be further improvements to droplet sampling and measuring techniques.

A comprehensive survey and critique of atomization literature was made by Lapple, et al (Ref. 5). The current state-of-the-art is probably best reflected by a comment made by these authors: "The best agreement was shown by the data for hydraulic swirl nozzles, where discrepancies were nominally not over twofold to threefold. The largest discrepancies, tenfold in some cases, were found for simple hydraulic nozzles. A large part of the discrepancy is attributed to shortcomings in the drop size analysis techniques, including sampling."

Most recently, extremely good results have been experienced in drop size and distribution measurements using the comparably new technique of laser holography photography. This method was selected by Matthews, Weurker, and Harje (Ref. 25) as offering the most promise in measurement of small particle size with minimum disturbance to the spray pattern. Their study consisted of two phases: (1) a review of spray measuring techniques and droplet data reduction method and (2) definitive testing with pulsed laser holography.

The laser holography photography technique has recently been used at AEDC to measure droplet size in high velocity gas streams. Davidson (Ref. 19) reported results of injecting a simulated defoliant into a 675-ft/sec velocity gas stream. These tests indicated excellent results in particle size measurements down to 10 microns. Smaller droplets can be resolved using a different lens combination.

SECTION IV RECOMMENDATIONS

Based on the results of this study program, the following items are suggested as methods for increasing general knowledge in the atomization field:

1. Improve or modify, if required, the laser holographic photography technique, and then establish accurate droplet size measurement methods. Document droplet size under varying injection conditions, and compare results with those of previous experiments using different measurement techniques. Develop new or modify old empirical relations if applicable.
2. Conduct tests to gain additional information on how the droplet size is affected by higher liquid flow rate and injection velocity in a high velocity air stream.
3. Conduct tests with high molecular weight polymer additives and record droplet size data for high-speed relative velocity atomization. Determine how additives affect the distribution.

4. Determine the effects of air turbulence on droplet size.
5. Conduct tests to determine droplet coalescence characteristics in more detail.

SECTION V SUMMARY

A review of several technical publications was made to determine the latest atomization technology and its applicability to production of 200- to 300-micron droplets in a 1000-ft/sec airstream. Several analytical and experimental studies were reviewed, and those considered most pertinent to this study are discussed. Results are summarized as follows:

1. Present state-of-the-art is not adequate to provide a dissemination technique that will meet specified requirements.
2. Chemical additives, which appreciably thicken and increase liquid viscosity, were successfully used to increase droplet size in a high velocity gas stream. This appears to be the only method that will produce the desired droplet size in an extremely high velocity gas stream.
3. There is a need for further development work, especially in the field of droplet sampling and measuring technique.
4. Aerodynamic forces at high velocity have more effect on resulting droplet size than liquid characteristics or injection configuration. A defoliant simulant was broken into droplets of approximately 21 microns when injected into a 675-ft/sec airstream; no noticeable effects of flow rate, injection pressure, or injector diameter were observed.

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APPENDIXES
I. ILLUSTRATIONS
II. DROPLET SIZE DEFINITION

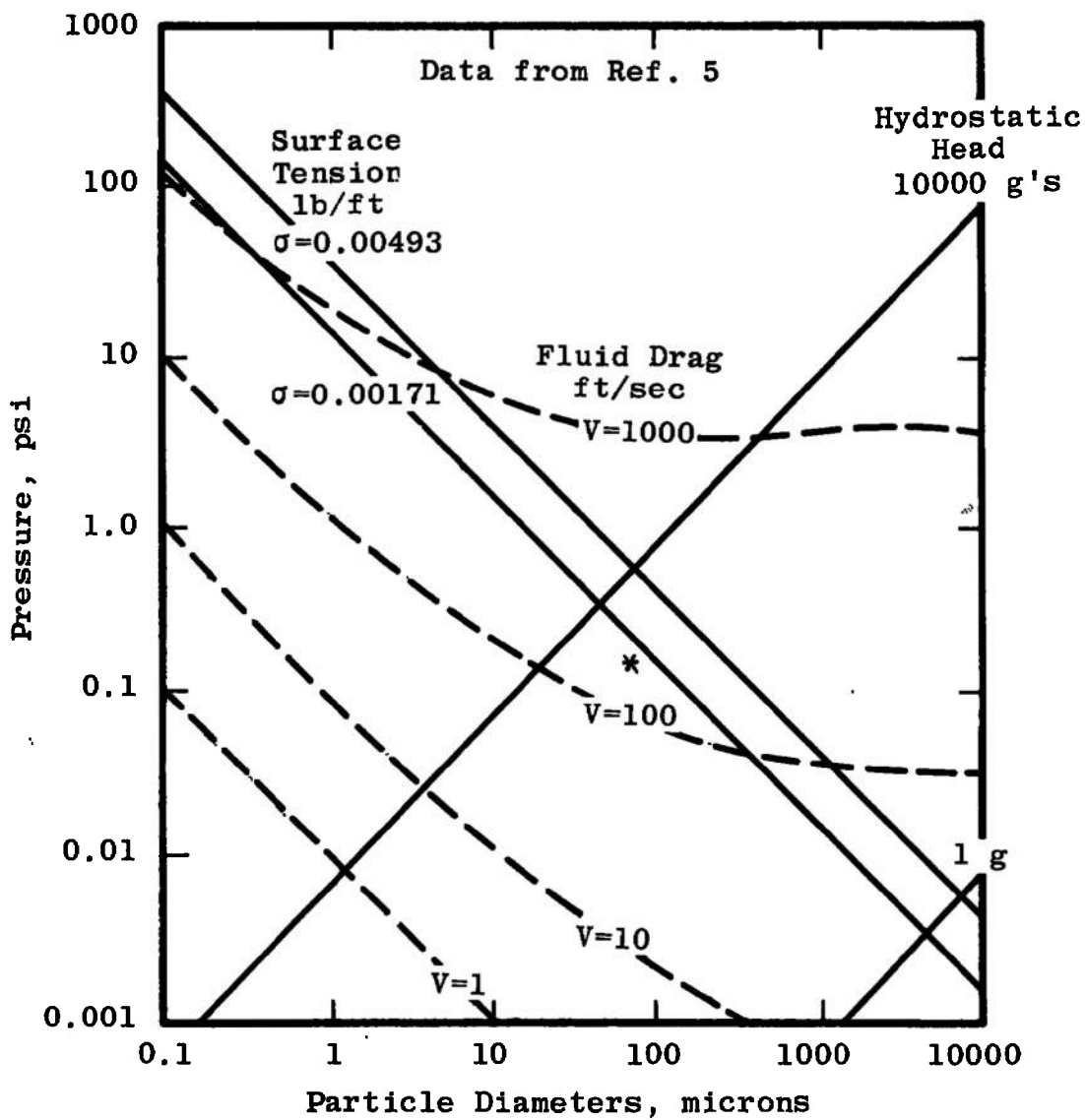


Fig. 1 Velocity and Gravity Effects on Droplet Size

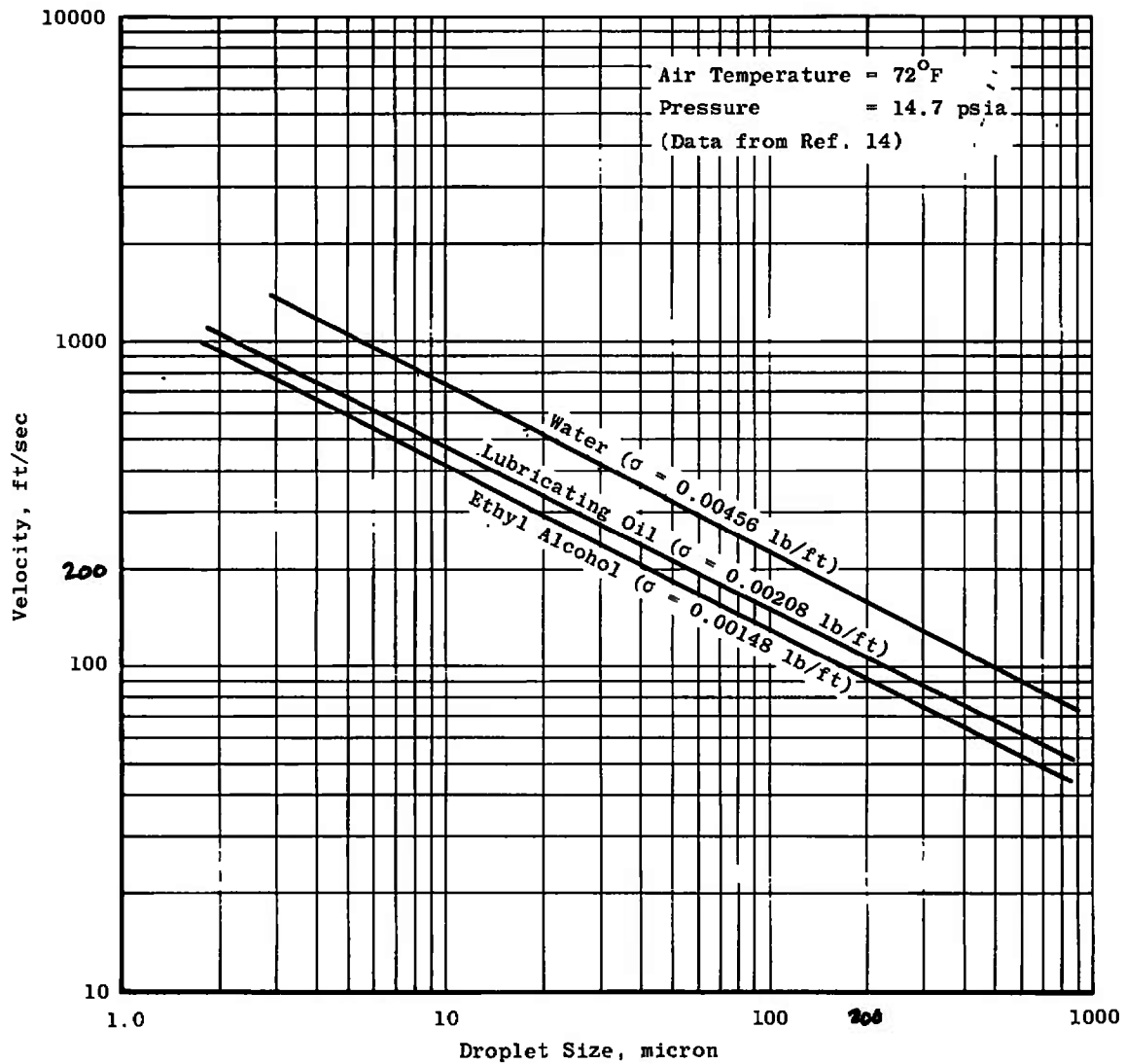


Fig. 2 Maximum Stable Droplet Diameter

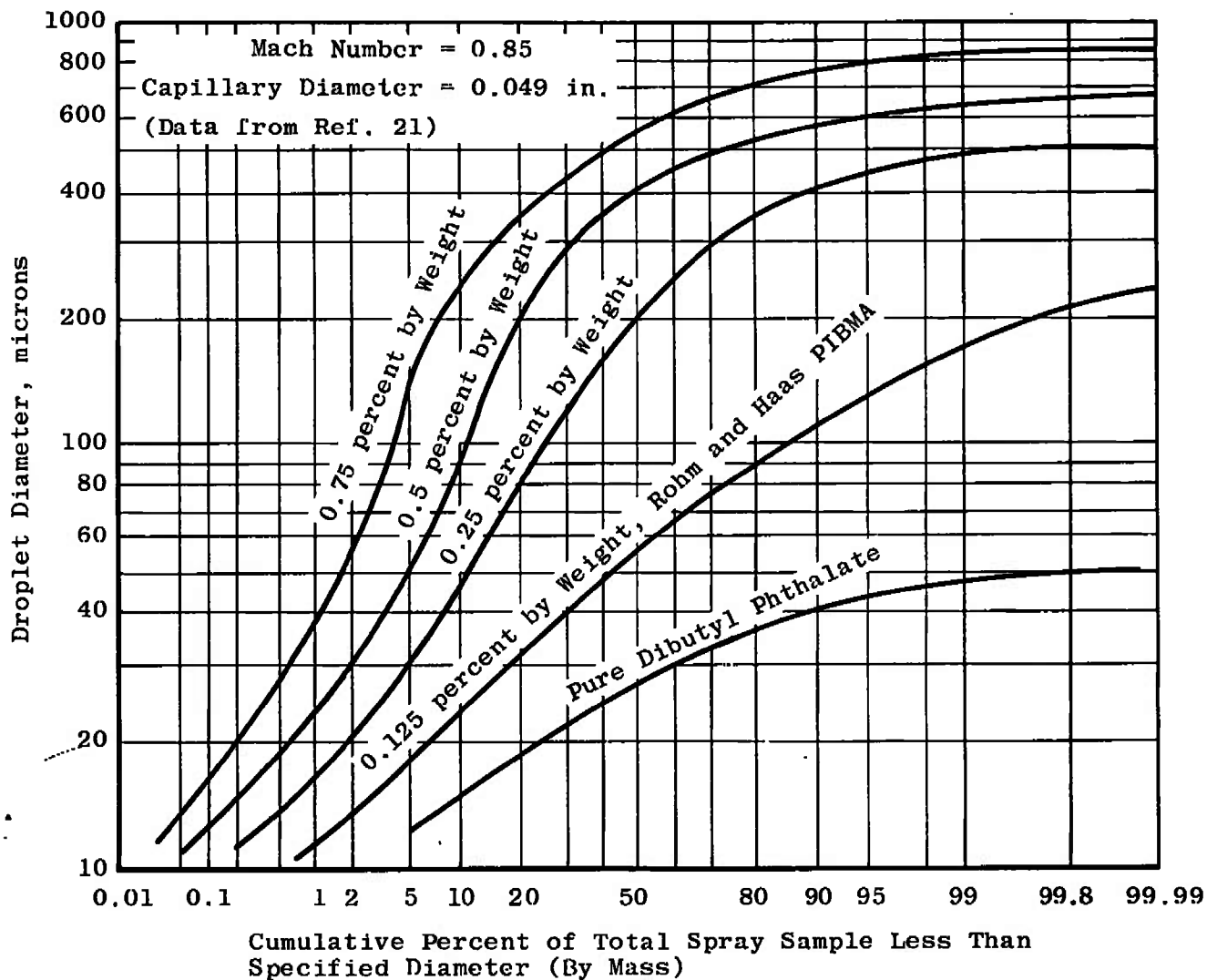


Fig. 3 Effects on Droplet Size of Rohm and Haas (PIBMA) Polymer when Added to Pure Dibutyl Phthalate

APPENDIX II

DROPLET SIZE DEFINITION

MEAN DIAMETERS

There are at least six types of mean diameters which may be used to represent a given spray distribution since the spray has four characteristics: (1) number of drops, (2) diameter, (3) volume, and (4) surface area of each drop. Equations that can be used to express mean diameters are:

Diameter-Number

$$D_{\bar{x}_n} = \frac{\sum X \Delta N}{\sum \Delta N}$$

ΔN = Number of drops of diameter X

Surface-Number

$$D_{\bar{x}_s} = \left[\frac{\sum X^2 \Delta N}{\sum \Delta N} \right]^{1/2}$$

Volume-Number

$$D_{\bar{x}_v} = \left[\frac{\sum X^3 \Delta N}{\sum \Delta N} \right]^{1/3}$$

Surface-Diameter

$$D_{\bar{x}_{sd}} = \left[\frac{\sum X^2 \Delta N}{\sum X \Delta N} \right]$$

Volume-Diameter

$$D_{\bar{x}_{vd}} = \left[\frac{\sum X^3 \Delta N}{\sum X \Delta N} \right]^{1/2}$$

Volume-Surface

$$D_{\bar{x}_{vs}} = \left[\frac{\sum X^3 \Delta N}{\sum X^2 \Delta N} \right]$$

MEDIAN DIAMETERS

In addition to mean diameters, median diameters are used to describe droplet sizes. The median value is defined as: if droplets are arranged according to size and "N" (total observations) is an odd number, the median is the value of the observation number $(N + 1)/2$; if N is an even number, the median is defined as the mean (average) of the observations $N/2$ and $(N + 2)/2$.

MASS MEAN OR MASS MEDIAN DIAMETERS

It is common for droplets to be mass weighted in terms of volume-number, i.e.,

$$d_{m.v.} = D_{m\bar{x}} = \left[\frac{\sum X^3 \Delta N}{\sum \Delta N} \right]^{1/3}, \text{ mass mean diameter or mean volumetric diameter}$$

where X is average droplet diameter;

$$d_{m.m.} \neq D_{m\bar{x}'} = \left[\frac{\sum X^3 \Delta N}{\sum \Delta N} \right]^{1/3}, \text{ mass median diameter}$$

where X is a median diameter.

I see no difference!!
something wrong.

by def., mass median diameter is that droplet dia. for which $1/2$ total liquid mass is contained in droplets with larger diameters, $d > d_{m.m.}$

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13. ABSTRACT A literature search was conducted to determine (1) if a nozzle system currently exists that would produce large monodisperse (200 to 300 micron) droplets when injecting liquids into a high-velocity airstream (up to 1000 ft/sec), (2) what extent current theories on Aerosol formation can be applied to high-speed dissemination of large, uniformly sized droplets, (3) to what extent these theories have been verified experimentally, and (4) whether additional theoretical and experimental investigations are necessary. A review of many technical publications indicated that the only method currently available for producing the desired droplet size in the specified air velocity is by adding high molecular weight polymers to the base liquid. Analytical and experimental results indicate that, in atomization by high-velocity gas, relative velocity is the most important parameter in determining resulting drop size. Secondary to velocity are viscosity, surface tension, gas and liquid density, and diameter of injector. Most all experimental investigators expressed the need for further research to improve atomization technology. In particular, the greatest need appears to be improvements in the technique for sampling and measuring small droplets. Distribution limited to U.S. Government agencies only; this report contains information on test and evaluation of military hardware; July 1971; other requests for this document must be referred to Armament Development and Test Center (DLNA), Eglin Air Force Base, Florida 32542.			

14.

KEY WORDS

LINK A

LINK B

LINK C

ROLE

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droplets

spray dispersion

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literature survey

atomization